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Memo

DATE: *April 17, 2005*

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the April 15, 2005 Meeting**

Present: Ilan Ben-Zvi, Andrew Burrill, Xiangyun Chang, Alexei Fedotov, Wolfram Fischer, Dmitry Kayran, Jorg Kewisch. Vladimir Litvinenko, William Mackay, Nikolay Malitsky, Edil Mustafin (GSI), Thomas Roser, Gang Wang (SUNY Stony Brook), Jie Wei.

Topics discussed: Cooling Experiment at CELSIUS, IBS-Suppression (IBS-S) Experiment at RHIC, and IBS Experiment with Normal RHIC Lattice.

Cooling Experiment at CELSIUS, IBS-Suppression (IBS-S) Experiment at RHIC, and IBS Experiment with Normal RHIC Lattice: At this meeting Alexei gave three presentations. First presentation was from cooling experiments he and Vladimir performed on CELSIUS, the second presentation was about intrabeam scattering (IBS) suppression in RHIC, while the third presentation was about IBS experiments with normal RHIC lattice.

The cooling experiments are an integral part of the R&D towards electron cooling of RHIC, with a main objective of benchmarking the suit of new codes which we are being developed in collaboration with other parties. The precise determination of the cooling (and heating) processes in RHIC is essential for a good, cost-effective design.
Among the experimental objectives, we have established the following goals:

- Accurate measurement of cooling force and code benchmarking.
- Benchmark new models of IBS required for accurate treatment of an ion distribution shrinking under cooling.
- Create condition expected in High Energy Cooler and study some issues like magnetized cooling with small cooling logarithm, effect of solenoid errors, etc.
- Benchmark the IBS heating rate at RHIC.

Good progress has been achieved in all of these objectives. In addition, we expect to proceed with measurements of the transition to non-linear plasma effects, where a large ion charge and large electron density lead to a reduction in the friction force, and establish that (as expected) this is not an issue for electron cooling of RHIC.

Below are Alexei's presentations.

Alexei's first talk

Beam experiments towards high-energy cooling

PLAN:

In present low-energy coolers:

 # 1 & 2: Accurate measurement of cooling force and code benchmarking.

 # 3: Benchmark new models of IBS required to treat accurately distribution shrinking under cooling.

 # 4 & 5: Create condition expected in High Energy Cooler and study some issues like magnetized cooling with small cooling logarithm, effect of solenoid errors, etc.

CELSIUS – experiments December'04-March'05

ALL proposed experiments were tried during December'04 and March'05 beam time.

Participants:

B. Galnander, T. Lofnes, V. Ziemann (TSL)

A. Fedotov, V. Litvinenko (BNL)

A. Sidorin, A. Smirnov (JINR)

Experimental data

1. B=0.1T, current dependence:

- measured cooling force for several electron currents:

Ie=500mA, 250mA, 100mA, 20 mA

2. Dependence on V_effective:

- measured for several values of tilt in both horizontal and vertical direction – both negative and positive directions.

- always recorded longitudinal and transverse sigmas to perform accurate convolution over distributions. Measured values are close to those predicted by BetaCool simulations

- did calibration of tilt angle with both BPM's and H^0 monitor

3. Measured "transient cooling" (IBS+COOLING) both for longitudinal profiles

4. Various values of B with various currents:

4.1) B=0.03T , Ie=500mA, 300mA, 100mA, 50 mA

4.2) B=0.04T – various currents

4.3) B=0.05T

4.4) B=0.06T

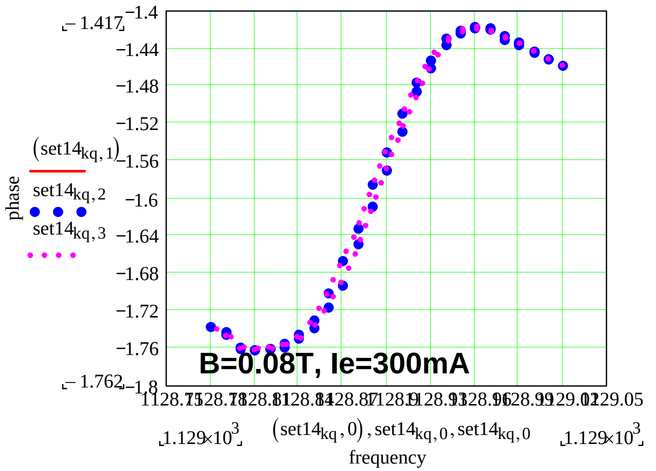
4.5) B=0.08T

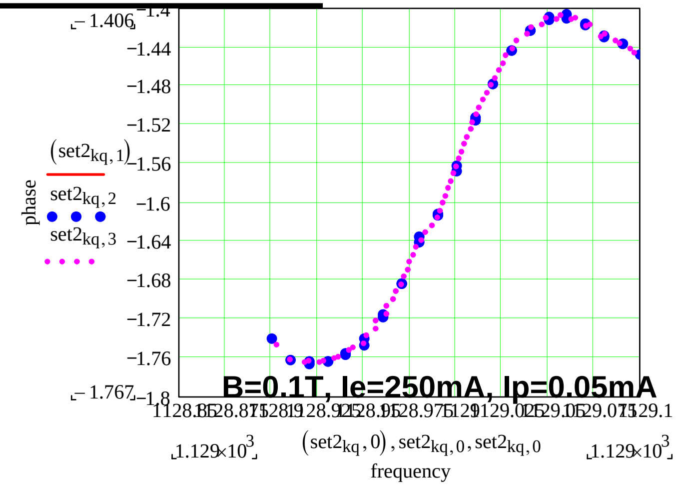
4.6) B=0.1T

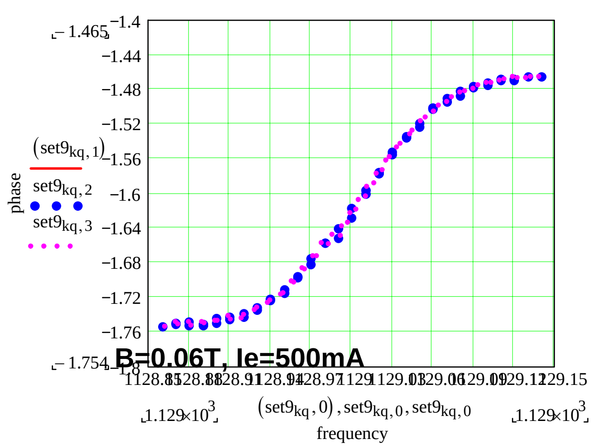
4.7) B=0.12T

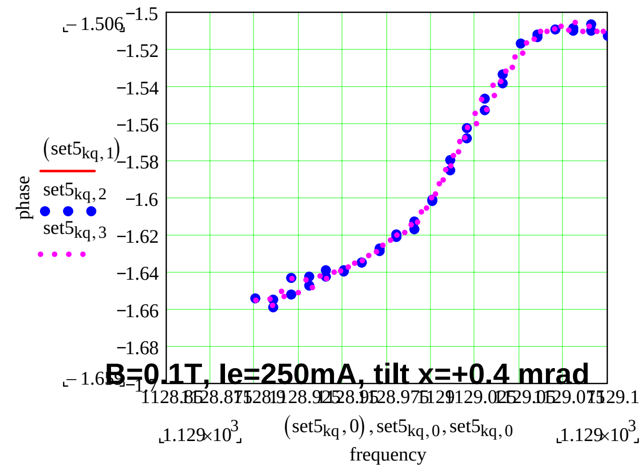
5. Effects of solenoid errors. Studies of V_effective.

10’s of measured friction force curves in various regimes (various currents, magnetic fields, alignment angles, magnetic field imperfections)









Summary

1. We completed the first set of basic experiments which should help to answer several questions regarding future high-energy magnetized cooling and have confidence in our computer simulations.

2. Depending on the analysis of the experimental data, some of the experiments (like effect of solenoid errors) may be repeated/improved at other coolers.

3. Other important experiments, like Z dependence, transverse cooling force, etc. will continue at other coolers.

Detailed analysis of each experiment is in progress

March 30 measurements: experiment with Neon ions: Z=10

- **Friction force was measured for Z=10 (Neon) ions at 2 energies with 2 currents of electron beam**

analysis of the data is in progress

Experiment #1

Experiment #1. **Benchmarking of friction force formulas with measurements. Study parameter dependence.**

Dependence of friction force on

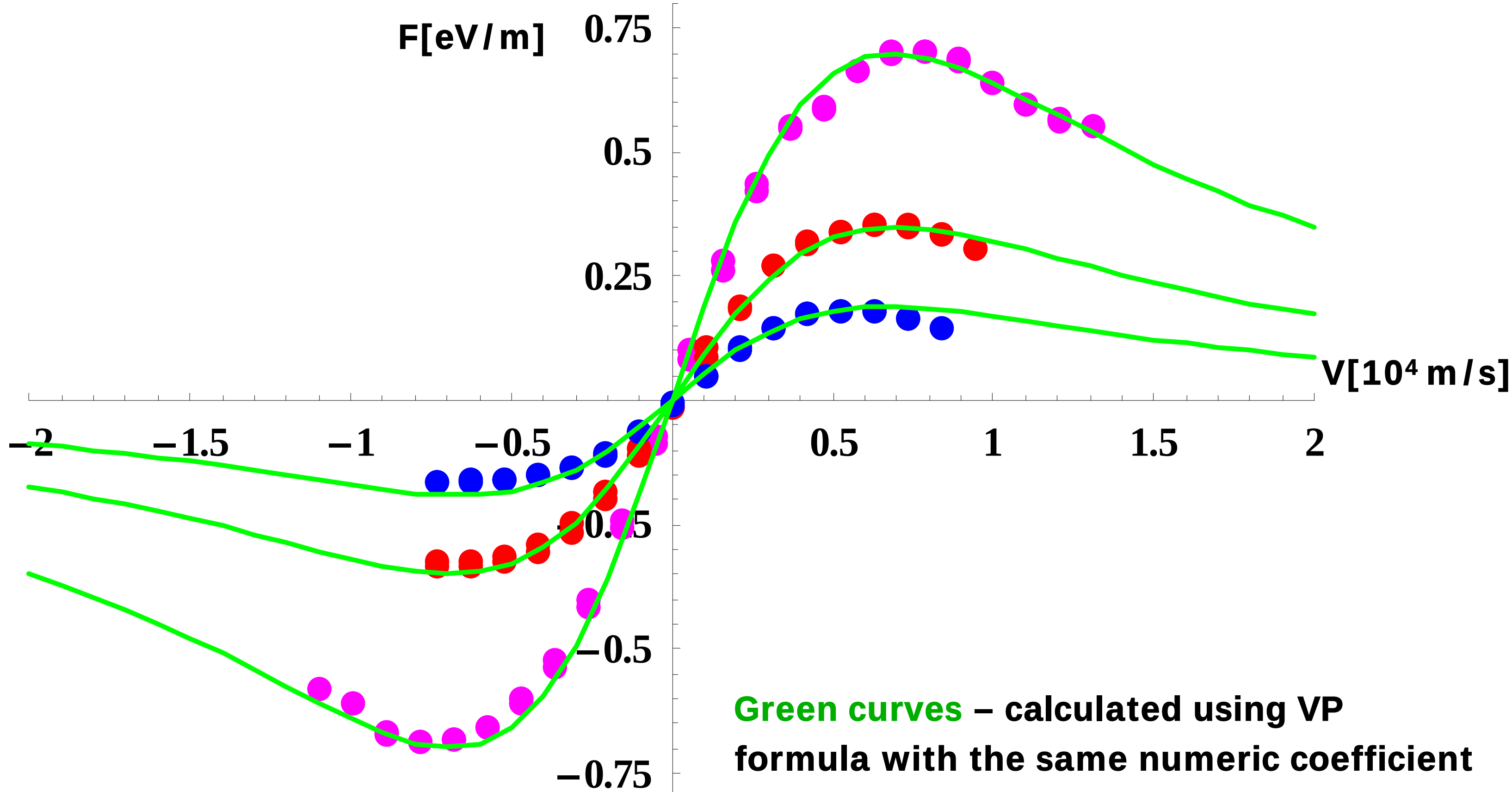
current of electron beam

V. Parkhomchuk's (VP) empiric formula

empiric formula (VP) – single-particle formula

$$\mathbf{F} = -\frac{1}{\pi}\omega_{pe}^2 \frac{(Ze)^2}{4\pi\varepsilon_0} \ln\left(\frac{\rho_{\max} + \rho_{\min} + r_L}{\rho_{\min} + r_L}\right) \frac{\mathbf{V}_{ion}}{\left(V_{ion}^2 + V_{eff}^2\right)^{3/2}}$$

March 5 data: B=0.12T electron current Ie=300mA (pink color), 117 mA (red) and 51 mA (blue)



Green curves – calculated using VP formula with the same numeric coefficient for Ie= 300, 117, 51 mA

B=0.12T – current dependence

1. Current dependence – friction force scales linearly with current/density – as expected from formula.
2. Numeric coefficient for the force is in agreement with the one in VP formula. Also, it can be adjusted to agree with Derbenev's coefficient which results in slightly different V_effective.
3. Note, that Coulomb logarithm depends on relative ion velocity and V_effective – fitting was done with such velocity-dependent logarithm.
4. Fitted V_effective has very weak current dependence (0.73-0.78*10^4 m/s) – logarithm is changing with current due to electron plasma frequency which determines maximum impact parameter.

Note

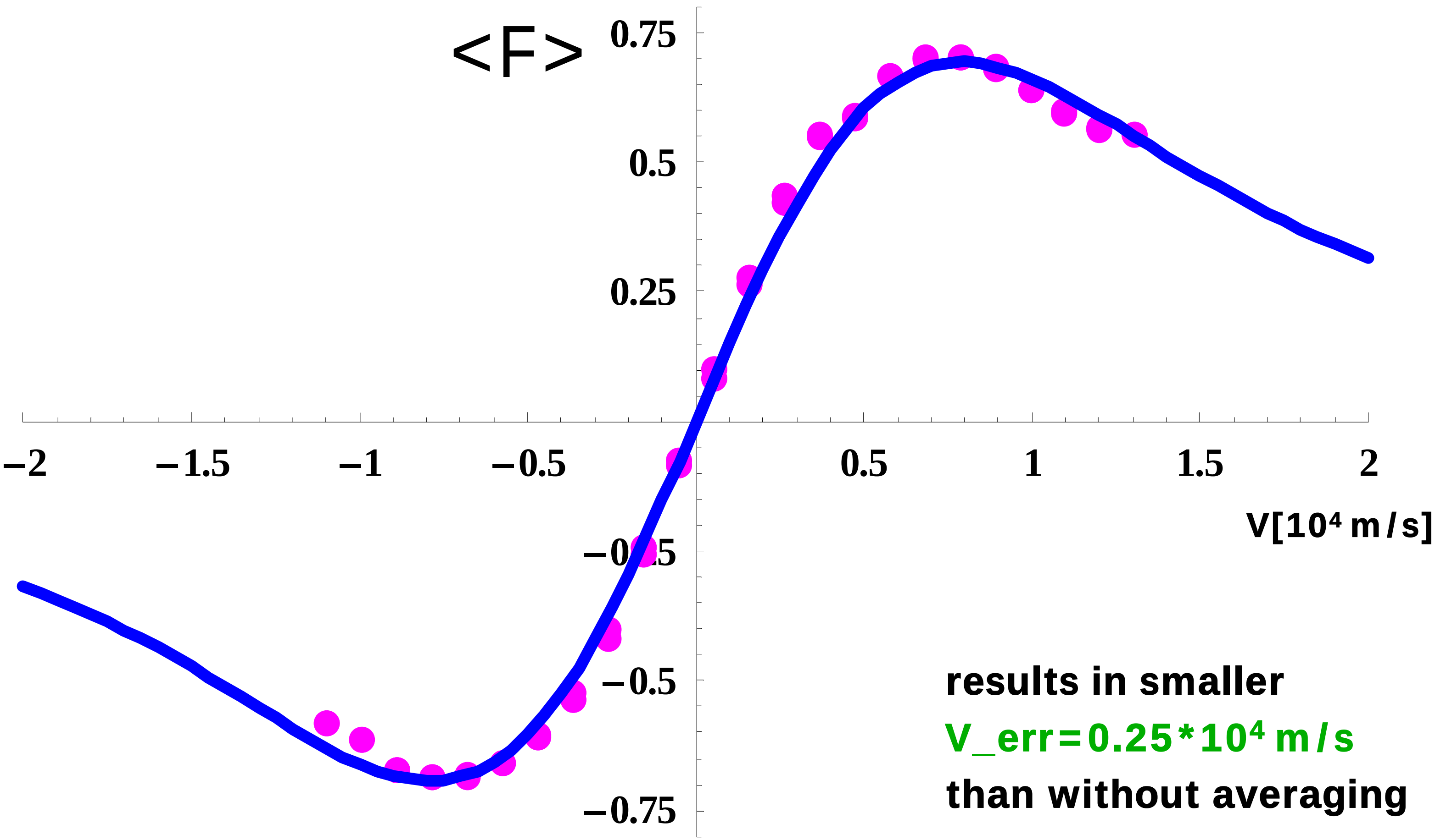
- Using single-particle formula allows to fit experimental data and extract V_effective.
- However, since rms velocity spreads of cooled proton beam are significant, found V_effective has contribution from this effect.
- The accurate procedure is then to measure rms velocities of the distribution and average single-particle formulas over the proton distribution.
- As a result, fitted V_effective for such averaged distribution is determined mainly by the solenoid imperfections (provided that contribution from the tilt and space charge are zero). For this reason, fitted in such a way V_effective, is referred to as "V_error".

Averaging over ion distribution

$$< F > = \frac{C \cdot L_c}{Int} \int_0^{\infty} \int_{-\infty}^{\infty} \frac{v_{\|}}{(v_{\perp}{}^2 + v_{\|}{}^2 + v_{err}{}^2)^{3/2}} \exp\left(-\frac{(v_{\perp})^2}{2\Delta_{\perp}^2} - \frac{(v_{\|} - v0)^2}{2\Delta_{\|}^2} \right) v_{\perp} dv_{\|} dv_{\perp}$$

$$Int = \int_0^{\infty} \int_{-\infty}^{\infty} \exp\left(-\frac{(v_{\perp})^2}{2\Delta_{\perp}^2} - \frac{(v_{\|} - v0)^2}{2\Delta_{\|}^2} \right) v_{\perp} dv_{\|} dv_{\perp}$$

March 5 data: B=0.12T, Ie=300mA (friction force averaged over proton distribution with measured rms velocity spread)

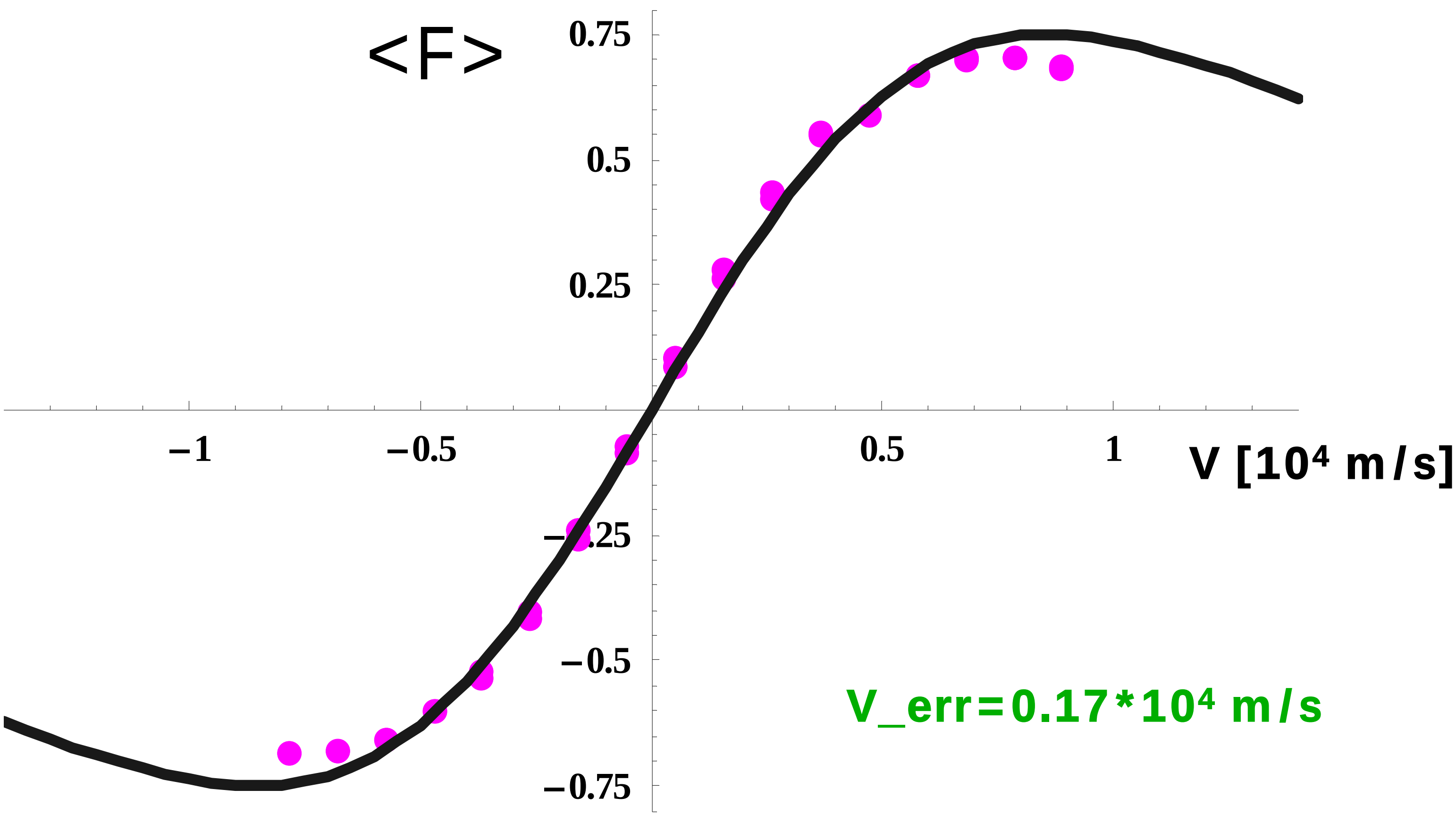


results in smaller
$V\_err=0.25*10^4$ m/s
than without averaging

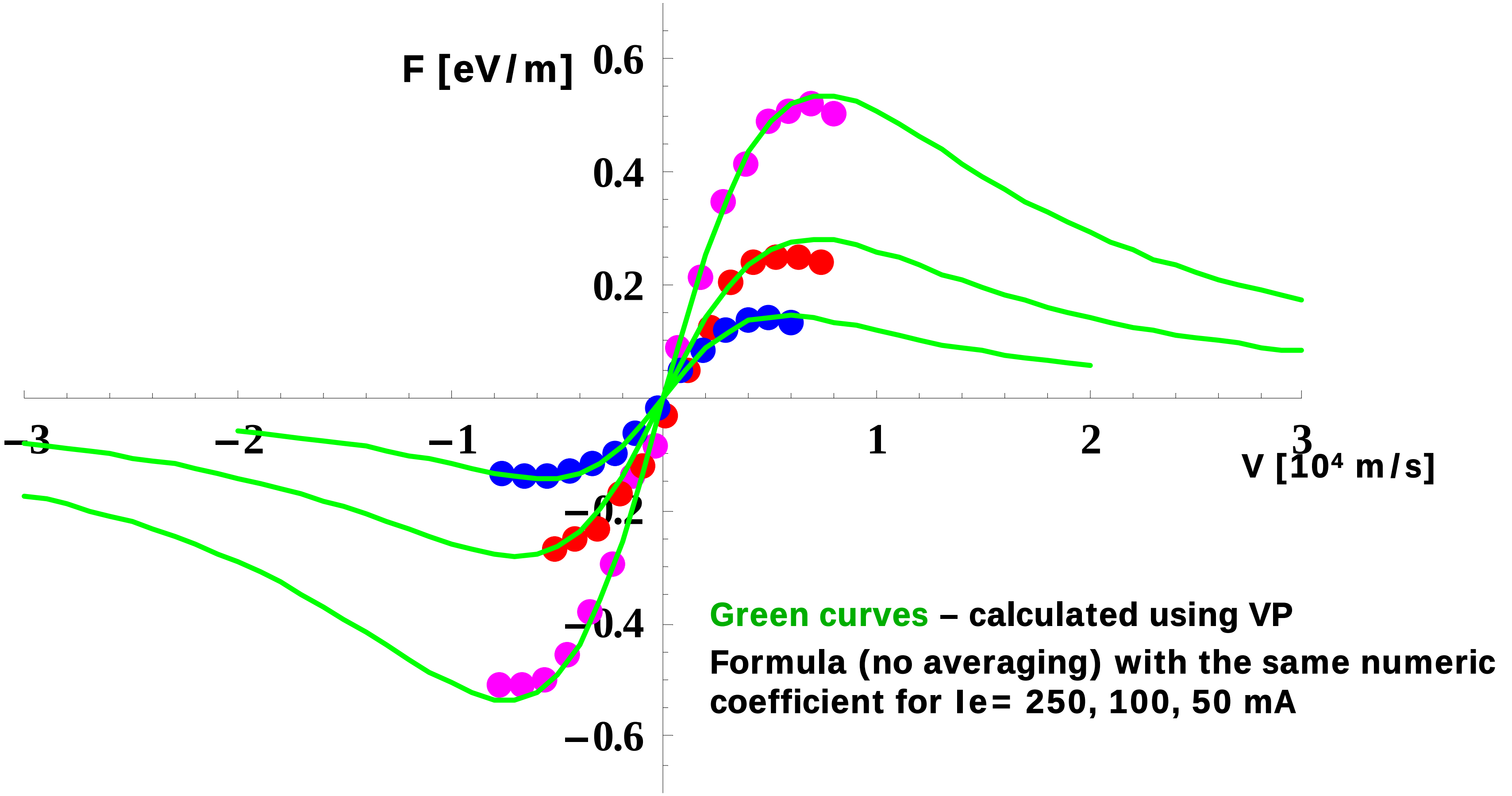
Averaging over ion distribution with changing logarithm

$$\langle F \rangle = \frac{C}{Int}\int_{0}^{\infty}\int_{-\infty}^{\infty} \frac{L_c(v_\perp, v_\parallel, v_{err})\cdot v_\parallel}{(v_\perp{}^2 + v_\parallel{}^2 + v_{err}{}^2)^{3/2}} \exp\left(-\frac{(v_\perp)^2}{2\Delta_\perp^2} - \frac{(v_\parallel - v0)^2}{2\Delta_\parallel^2}\right) v_\perp dv_\parallel dv_\perp$$

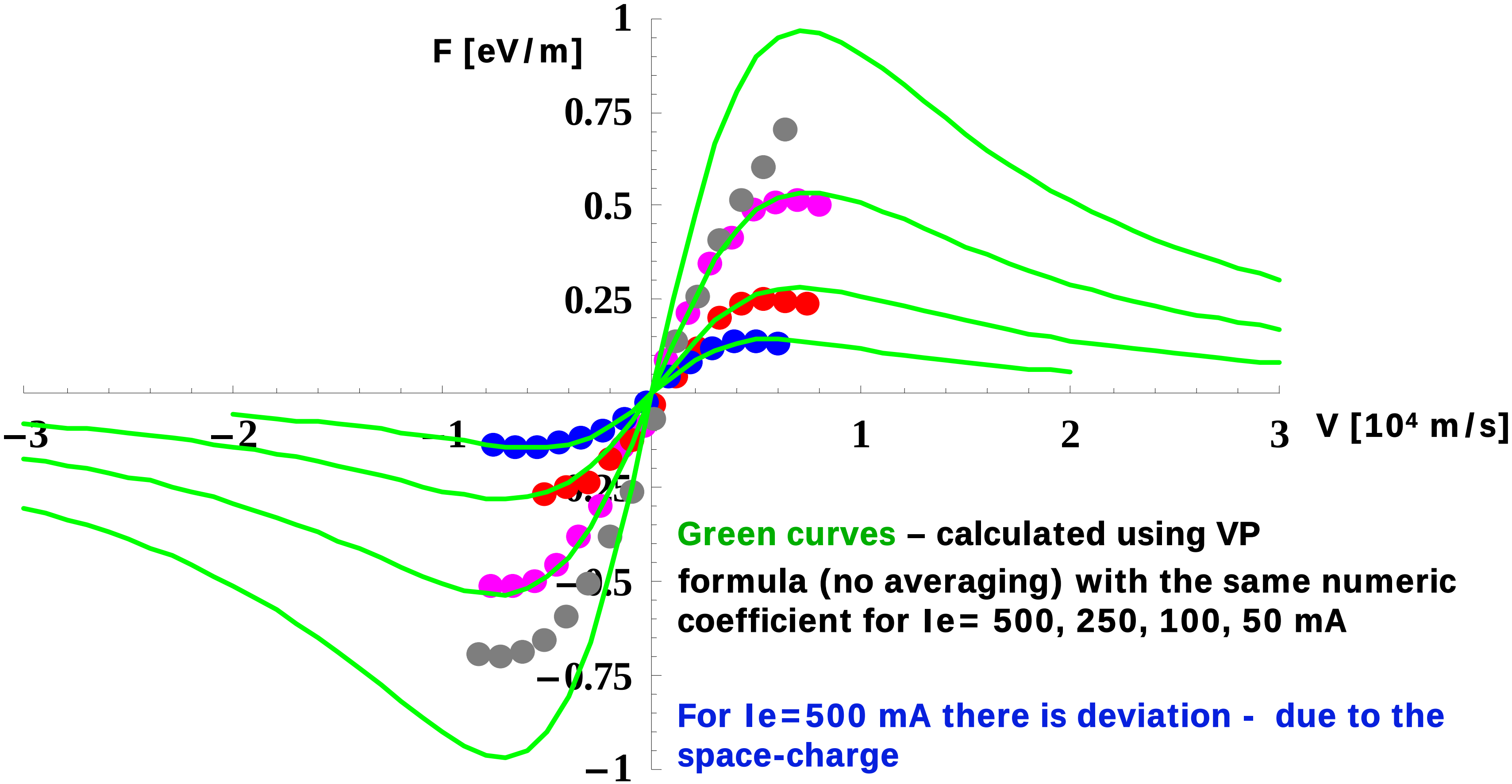
With logarithm under the integral



March 2 data: B=0.1T
electron current Ie=250 (pink color), 100 (red), 50 (blue) mA



March 2 data: B=0.1T
Ie=500 (gray), 250 (pink), 100 (red), 50 (blue) mA



Green curves – calculated using VP formula (no averaging) with the same numeric coefficient for Ie= 500, 250, 100, 50 mA

For Ie=500 mA there is deviation - due to the space-charge

Electron current Ie=500mA

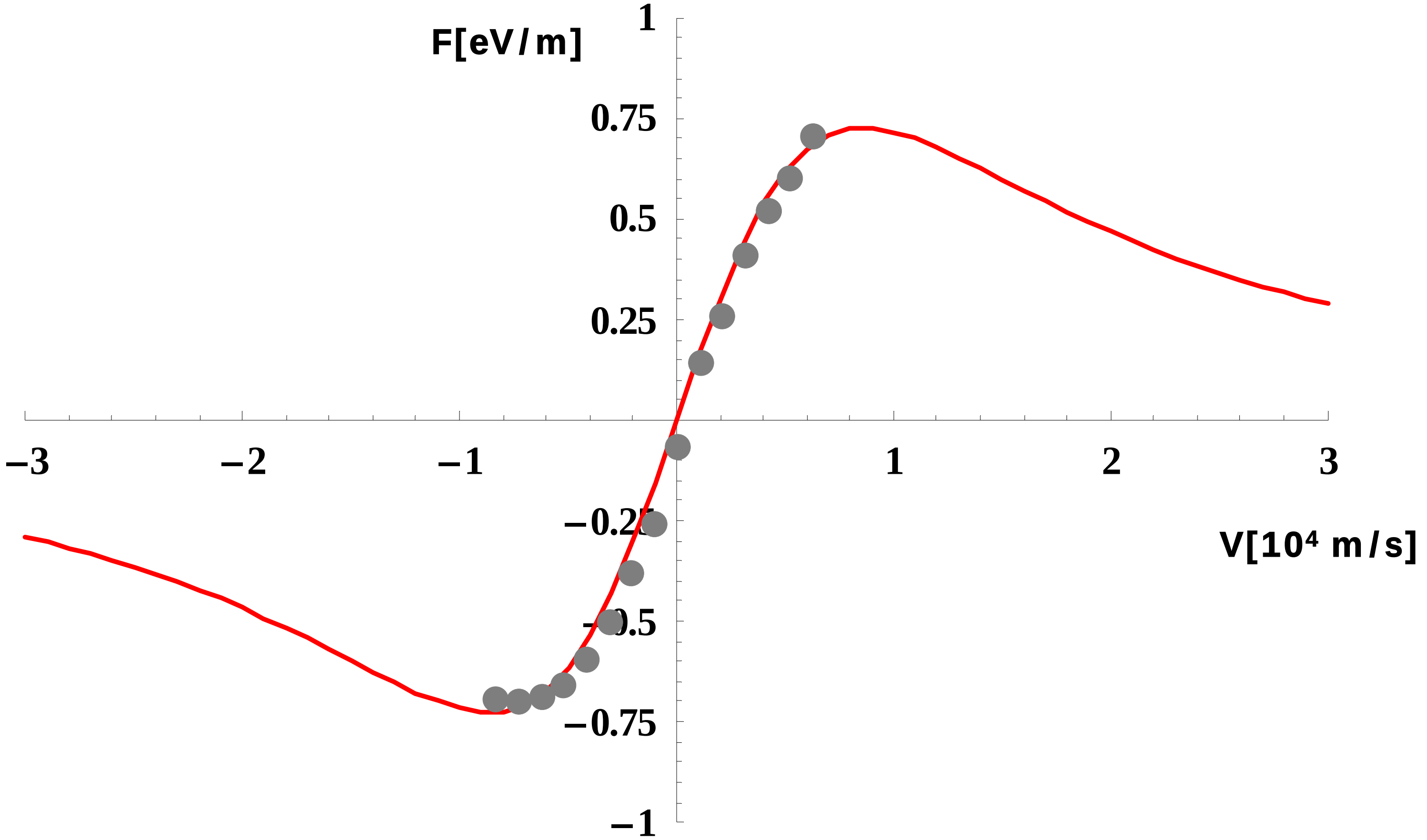
For high currents of electron beam space-charge of the cooling electron beam become important:

The electron drift in crossed fields – the electric and magnetic fields of the electron beam and longitudinal magnetic field of the cooler:

$$v_d = \frac{2I}{B\beta\gamma^2}\frac{r^*}{a^2}$$

For measured distribution of the proton beam for the case under comparison (March 2, set#23, B=0.1T, Ie=500mA)- V_drift=6-7*10^3m/s – which is an additional contribution to V_effective in the cooling force formulas.

March 2 data: Ie=500mA, B=0.1T – formula vs experiment with additional contribution to V_effective from V_drift



Alexei's second talk

IBS calculations for Beam Experiment with higher phase advance (γ=33 GeV).

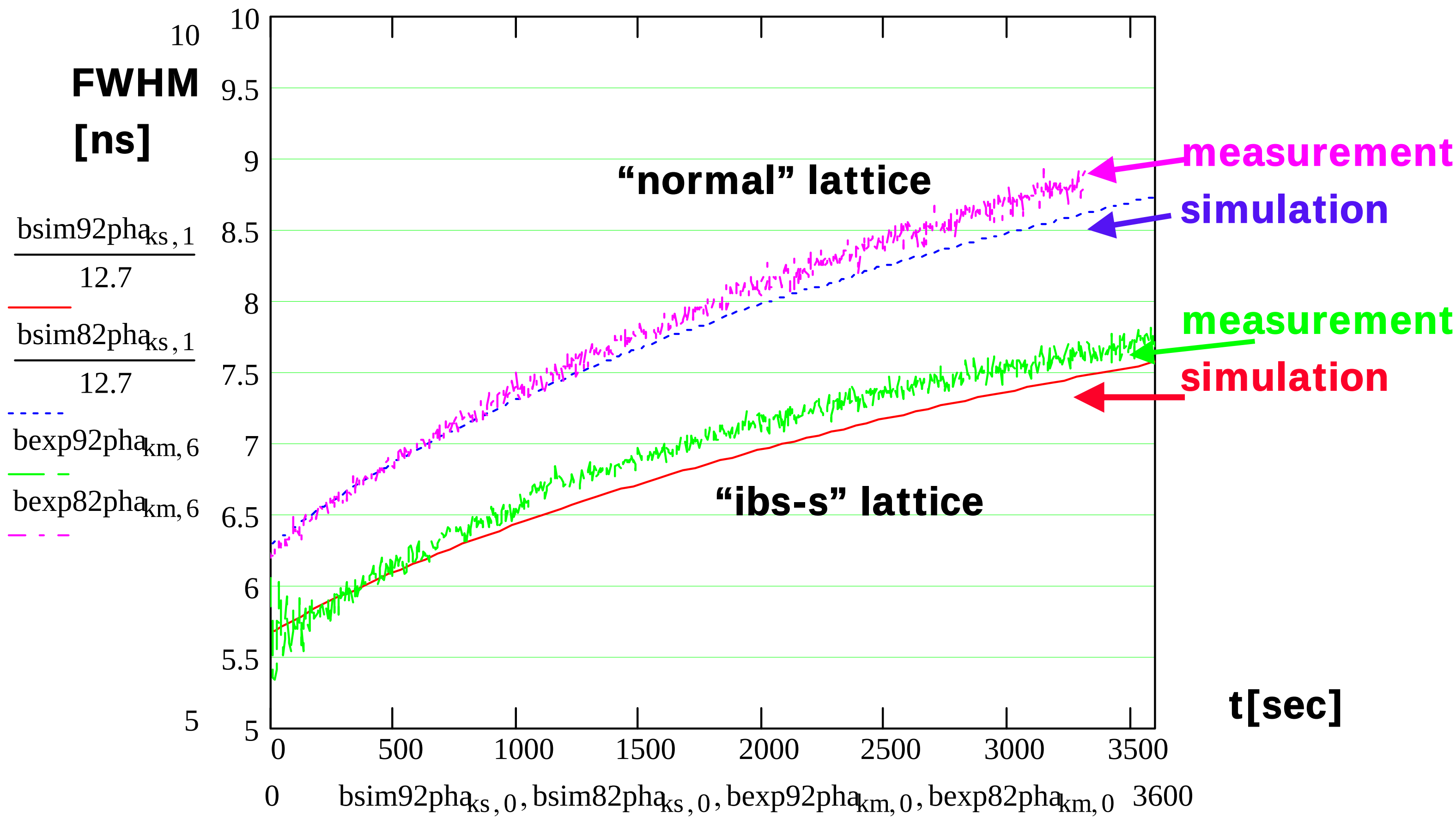
IBS calculation using BETACOOL code (based on exact Martini's model with all lattice derivatives).

Simulation for parameters of bunch in bucket #100:

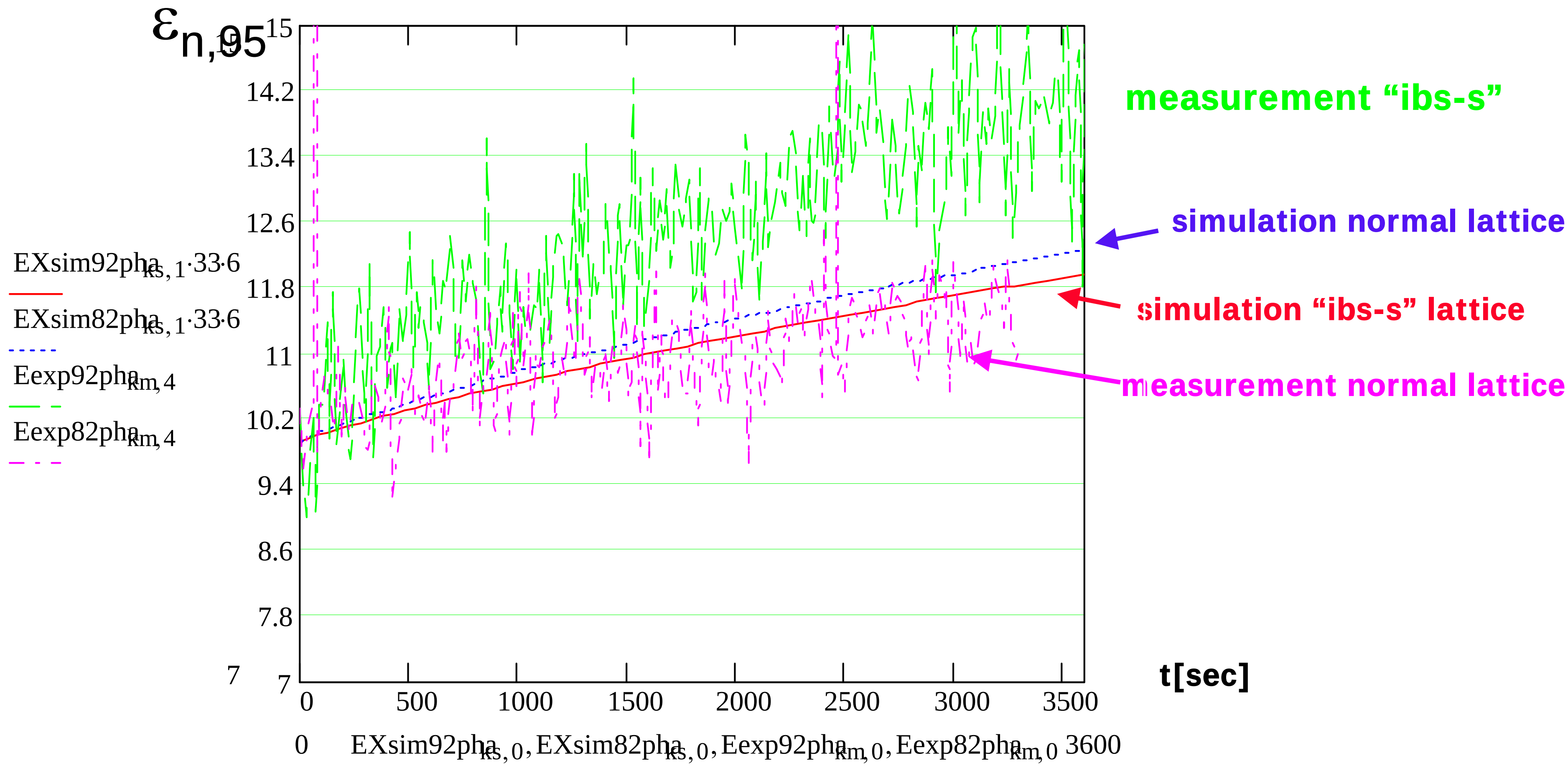
Cu ions, h=360, V=300kV, no collisions, bucket #100

1. **December'04: it was shown that "ibs-s" lattice gives larger emittance growth at injection energy – to demonstrate advantage of the new lattice experiments needs to be done at 100 GeV.**
2. **March'05: during the ramp development for the new lattice it was decided to do experiment at 30GeV. Simulations showed that if experiment is very clean than it is still possible to see slightly less emittance growth with the "ibs-s" (higher ph. adv.) lattice.**
3. **For the experimental data (March 2005, fill #6513 & 6529) simulations are shown on the next slides.**

Bunch length growth (bucket #100)



Emittance growth (bucket #100)



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Observation

1. Bunch length growth agrees well between simulations for both "normal" and "ibs-s" lattice.

2. Emittance growth agrees well between simulations and measurement for "normal" lattice.

3. For the parameters of experiment, emittance growth for the "ibs-s" lattice should be almost the same as for normal lattice. This suggests that emittance growth for measured "ibs-s" lattice is due to something else which is correlated with unexpected beam loss.

Alexei's third talk

IBS experiment for Cu ions: February 7, 2005

W. Fischer, A. Fedotov, J. Wei, S. Tepikian, R. Connolly et al.

1. **At injection:**

   yellow – coupled

   blue - decoupled

2. **IPM worked in both planes in both rings**
3. **At store: measured dQmin: both rings coupled.**

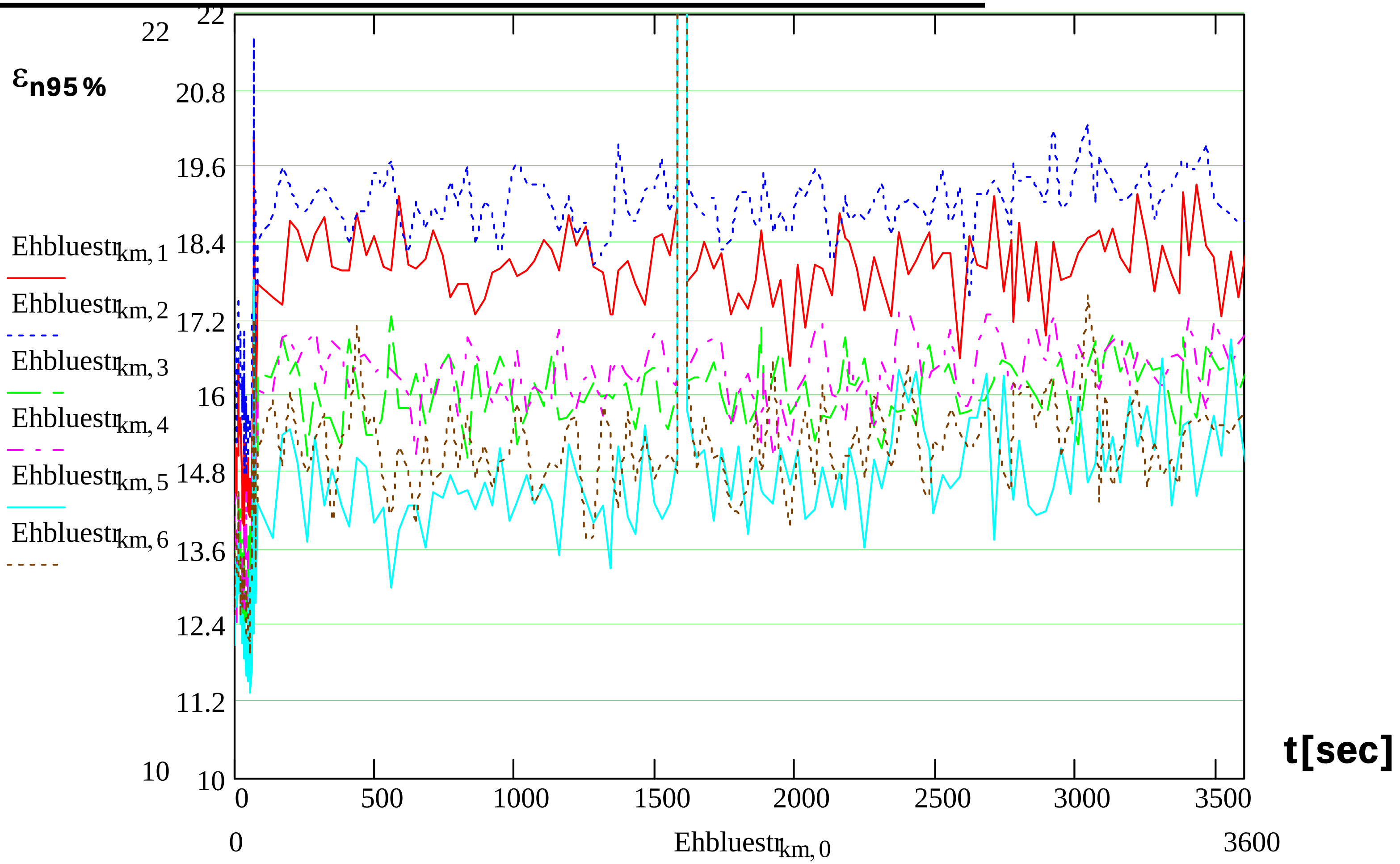
Preliminary analysis (Fedotov, Wei): April 14, 2005

IBS calculations for Beam Experiment fill #6102 at store energy 100 GeV with coupling

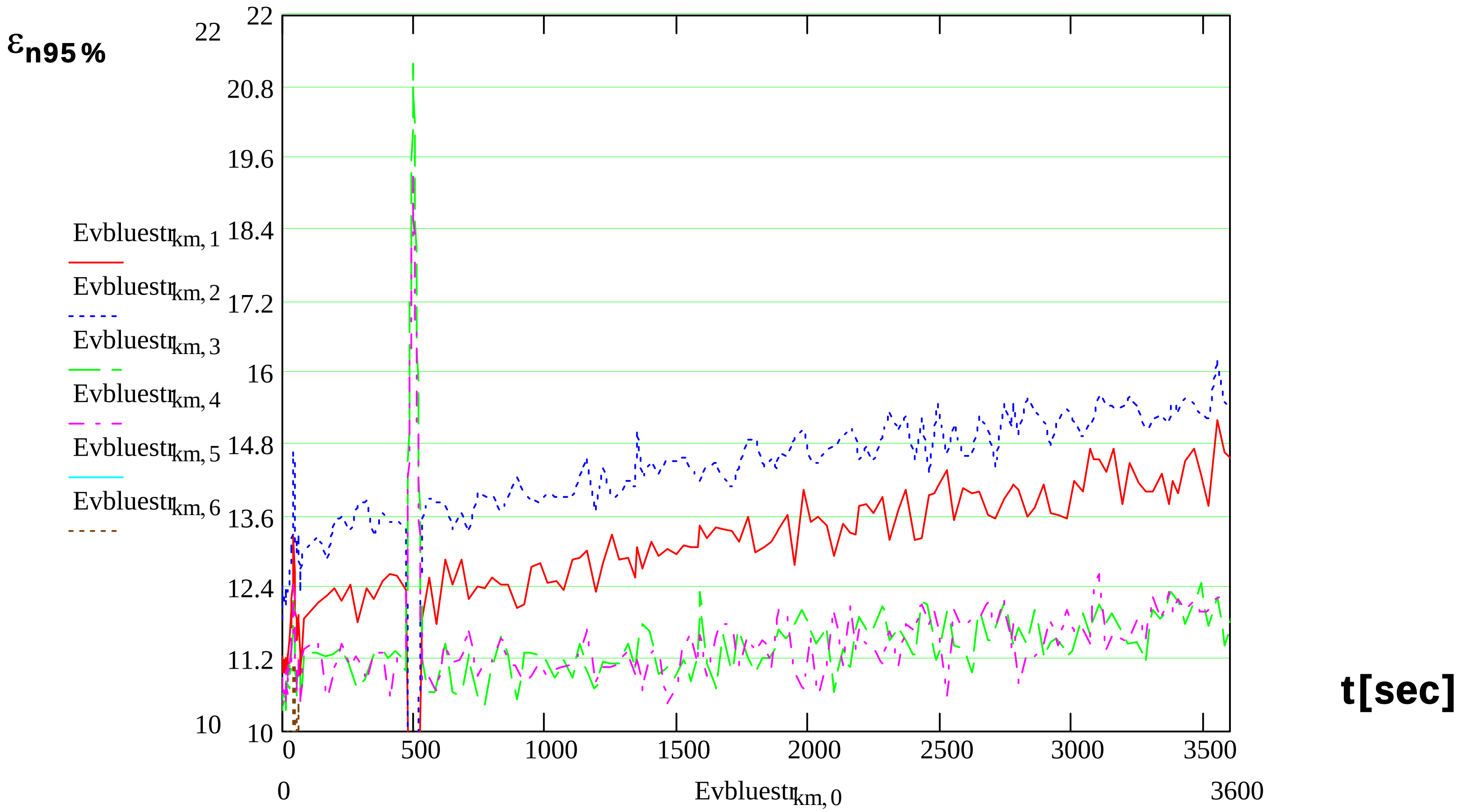
IBS calculation using BETACOOL code (based on exact Martini's model and real RHIC-5 lattice).

Cu ions, h=360, V=300kV, no collisions

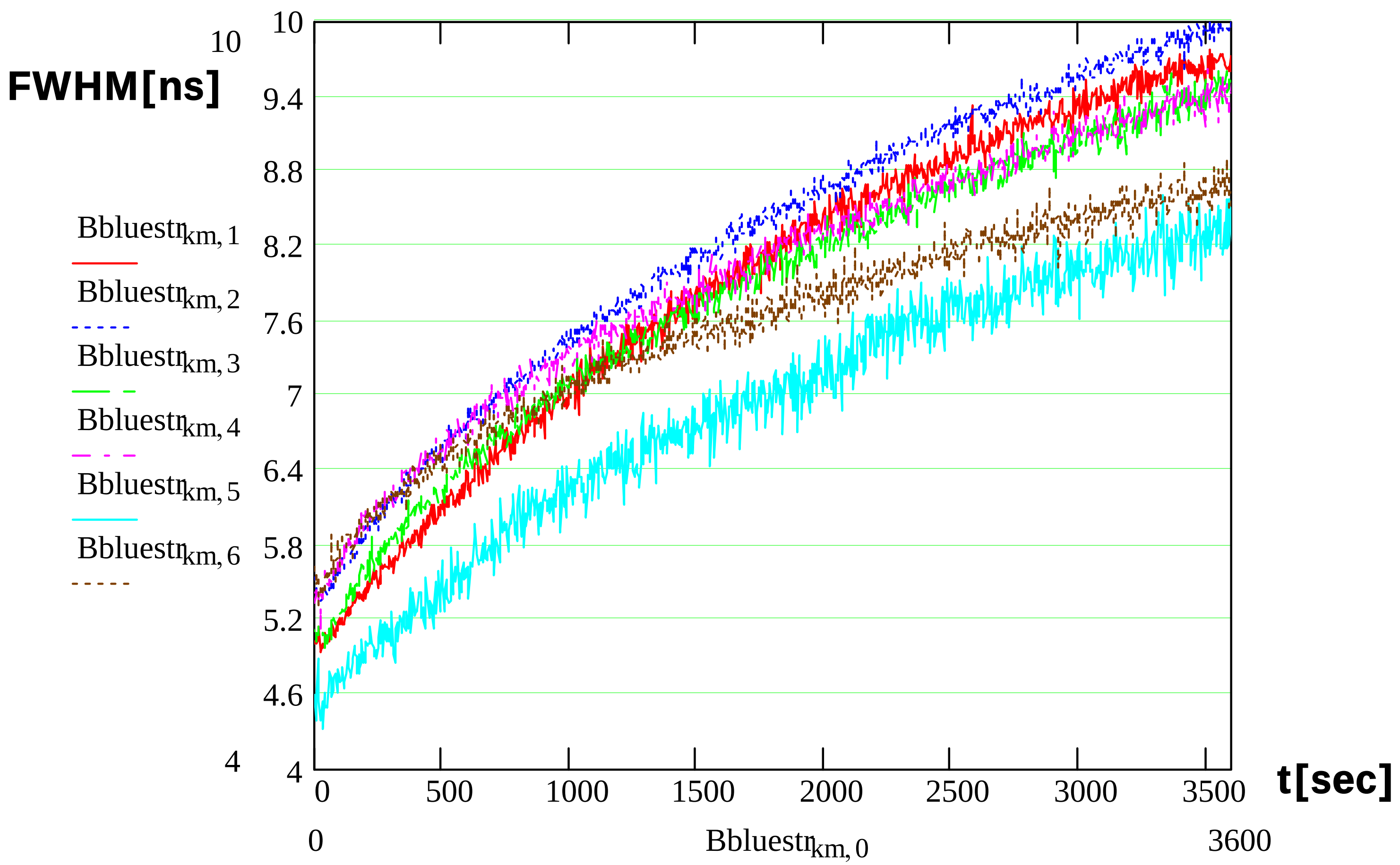
Horizontal emittance for six buckets in BLUE



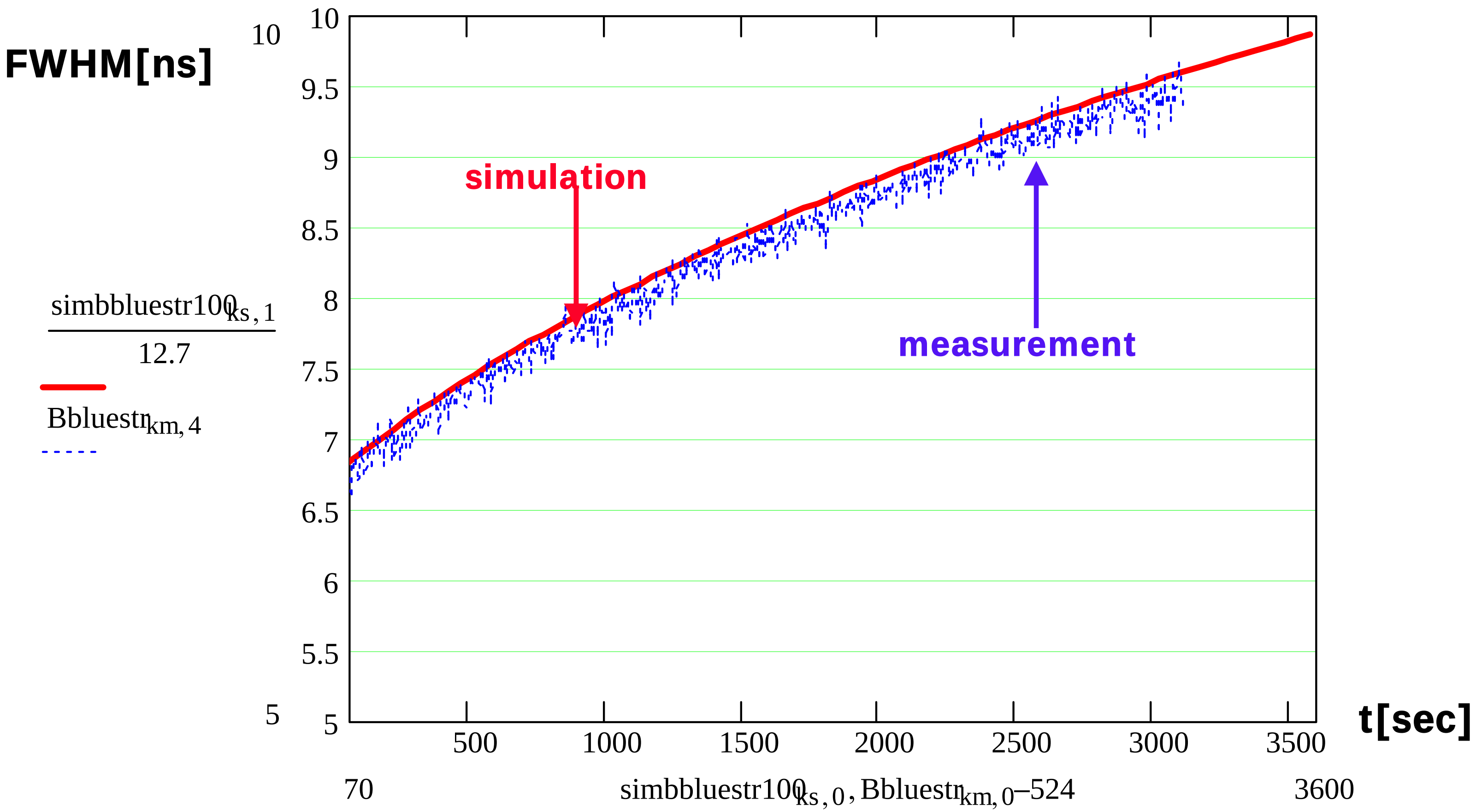
Vertical emittance for six buckets in BLUE



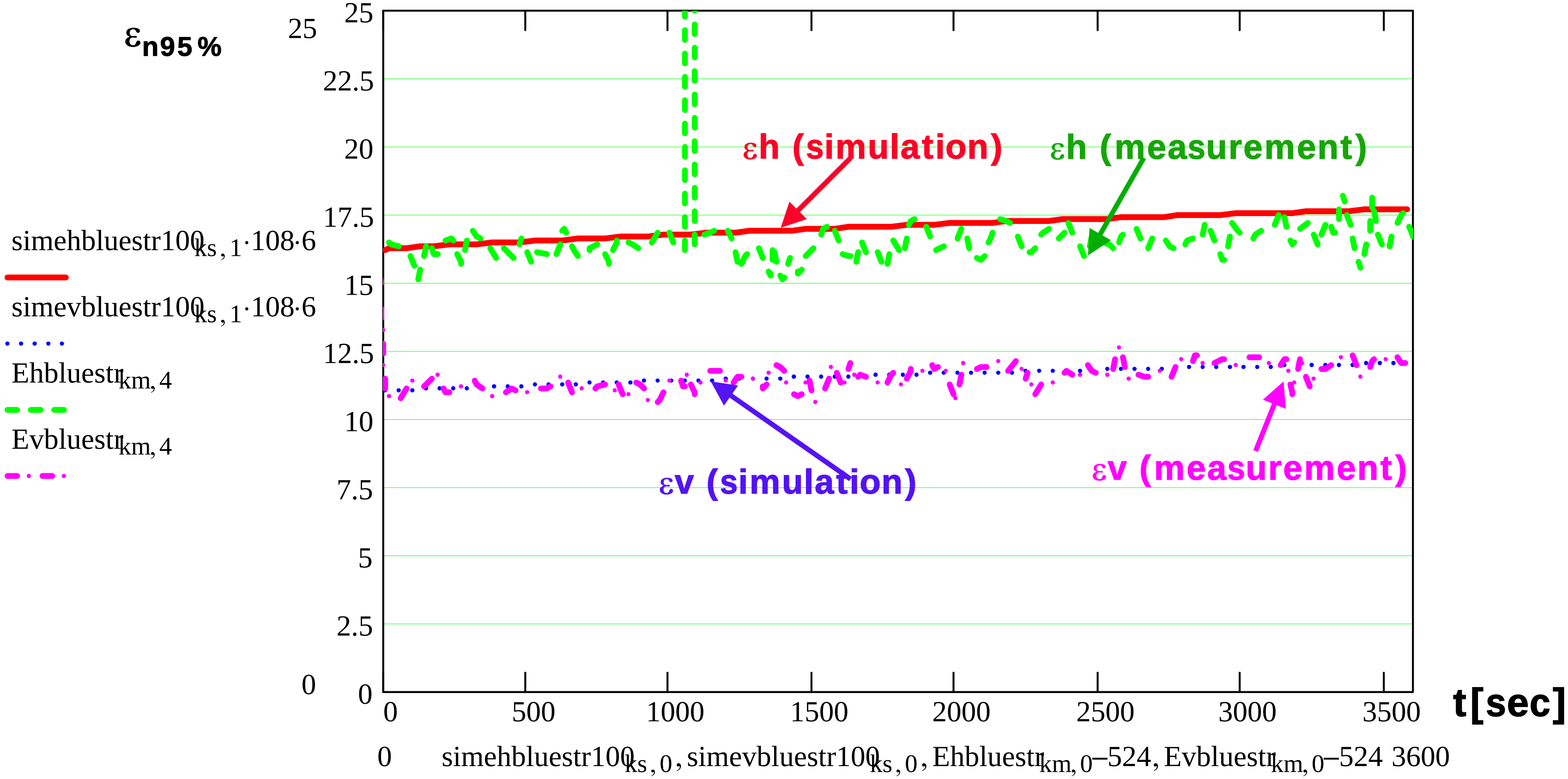
Bunch length for six buckets in BLUE



Bucket #100 in BLUE (N=2.9e9)



Bucket #100 in BLUE (N=2.9e9)



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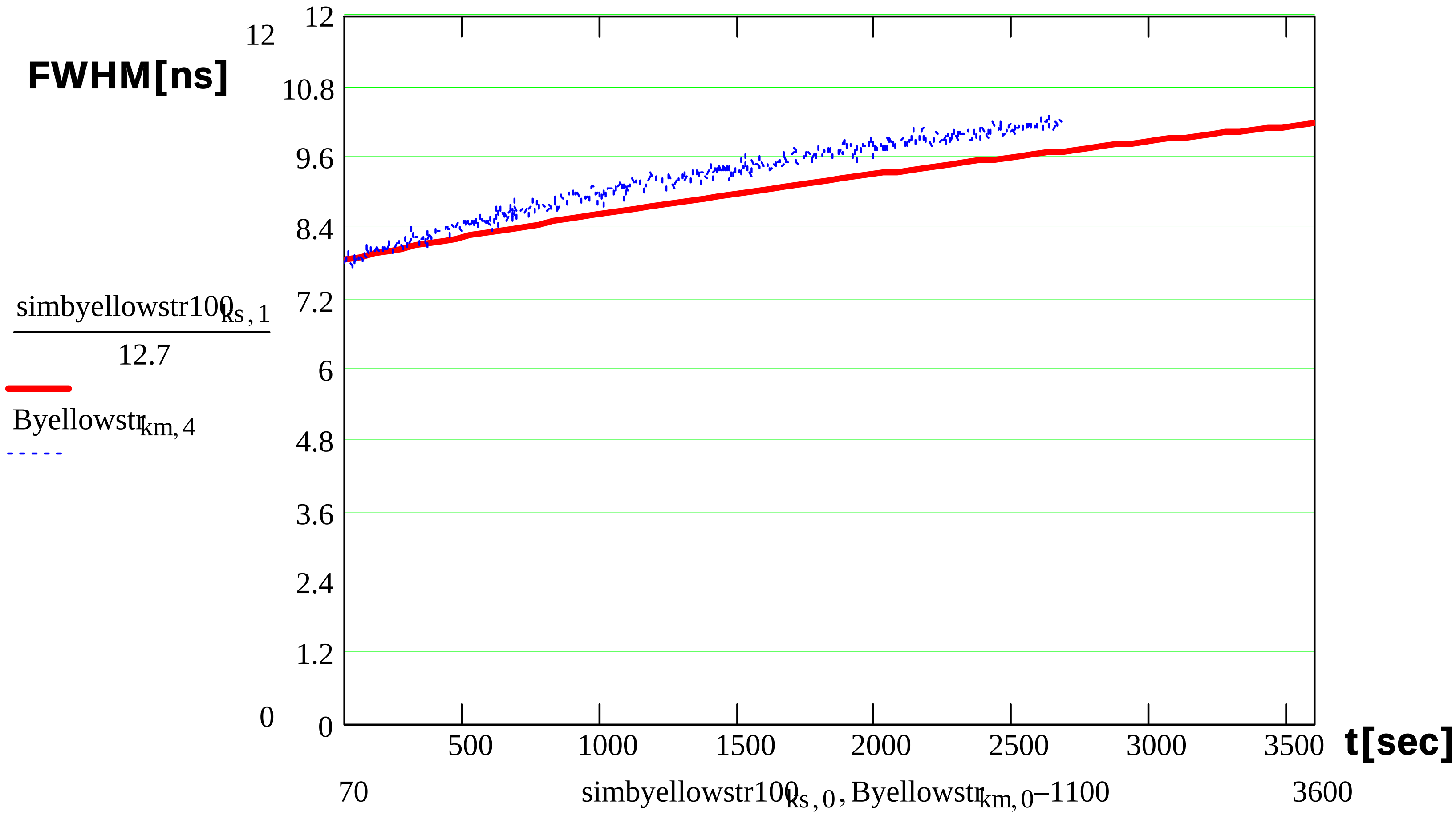
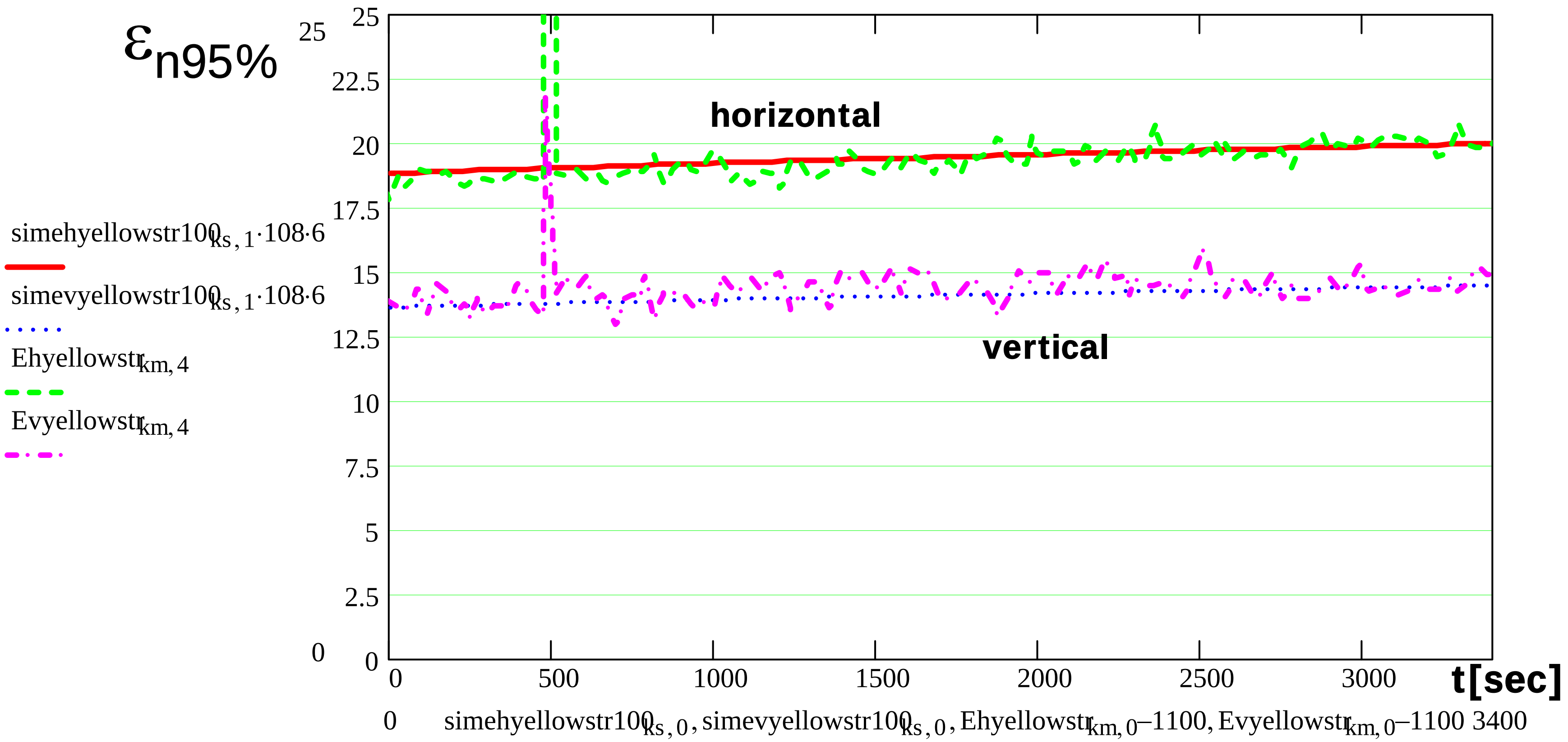
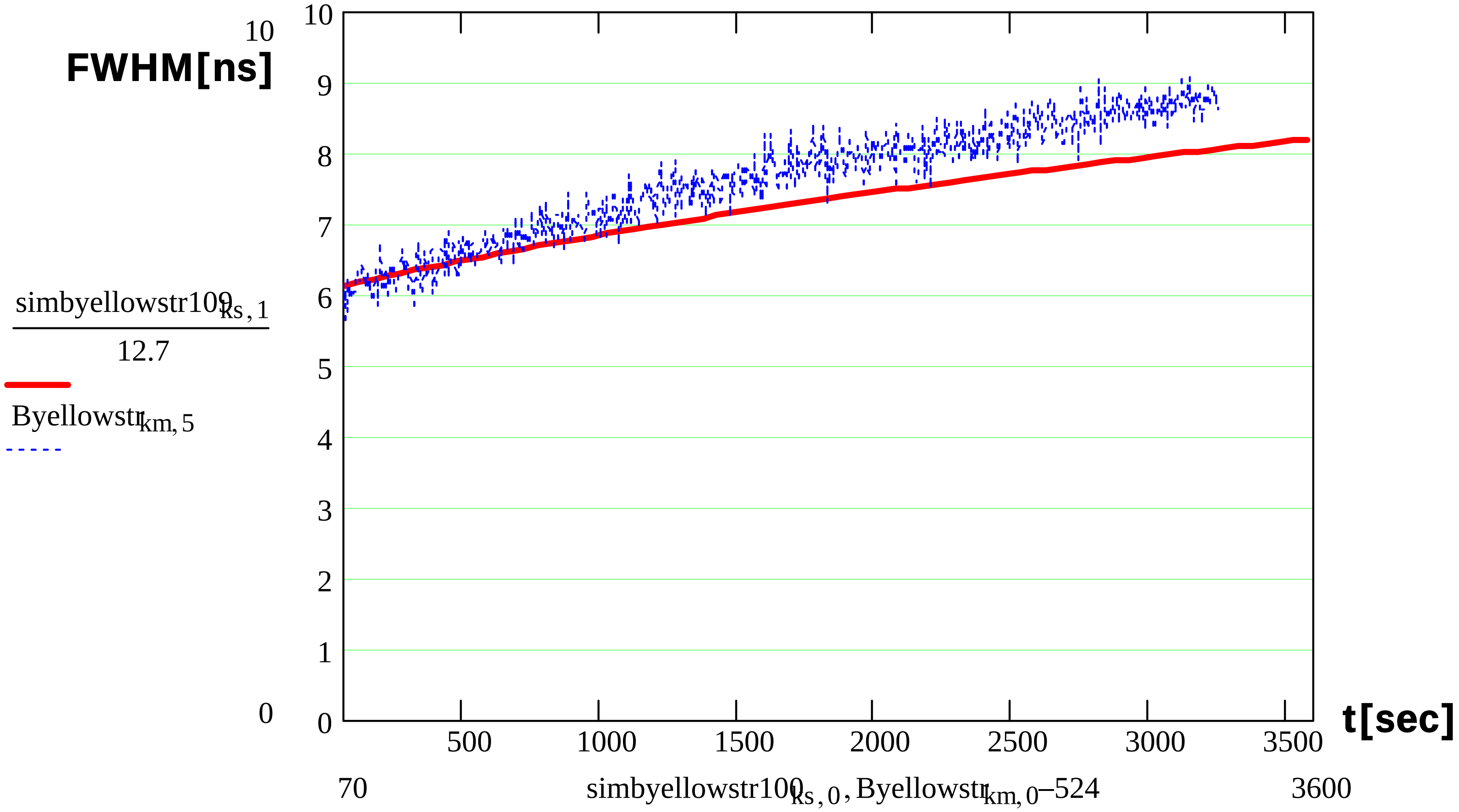
Bucket #100 in YELLOW (N=3.3e9)



Bucket #100 in YELLOW (N=3.3e9)



Bucket #109 in YELLOW (N=1.2e9)



Bucket #109 in YELLOW (N=1.2e9)